# Past as Prologue: Swarm and the Decade of Geopotential Field Research

The Decade of Geopotential Field Research, inaugurated in 1999 with the launch of the Danish satellite Ørsted on 23 February, was designed as an international effort to promote and coordinate continuous monitoring of geopotential field variability in the near-Earth environment. The CHAMP, GRACE, SAC-C, and most recently, GOCE, satellites have combined to generate an unprecedented wealth of data on Earth's magnetic and gravity fields. Interpretation of the new magnetic data from the Decade has led to improvements in our knowledge of the fast changing small scales of the Earth's magnetic field, and given us the first World Digital Magnetic Anomaly Map. The data, and associated theory and modeling work, also led to the discovery of new processes with satellite magnetic signatures, amongst them oceanic tides, ionospheric pressure gradient currents and the magnetic signatures of ionospheric plasma irregularities, and serpentinized mantle overlying subduction zones.

Expected to reenter the atmosphere by the end of 2009, CHAMP will be succeeded around 2010 by Swarm, the 5th Earth Explorer mission in ESA's Living Planet Programme (Fig 1a). The mission aims at measuring the Earth's magnetic field with unprecedented accuracy. This will be achieved with a constellation of three polar orbiting satellites, two at low altitude, measuring the east-west gradient of the magnetic field, and one at higher altitude in a different orbital plane. Swarm satellites will carry instrumentation to measure the vector and scalar magnetic fields, electric fields and plasma parameters, non-gravitational accelerations, and the position with GPS. The constellation is designed to maximize the scientific return in the areas of core dynamics, lithospheric magnetization, and 3-D mantle conductivity. It will also investigate electric currents flowing in the magnetosphere and ionosphere, quantify satellite drag in the upper atmosphere and search for the magnetic signature of ocean circulation. Expected results from Swarm and new results from CHAMP and Ørsted will be presented at the 2nd Swarm International Science Meeting, to be held at GFZ in Potsdam, Germany, from 24-26 June 2009.

Venus and Mars are often considered Earth's twins. But when it comes to Earth's magnetic field, it is to Mercury that we look first. Mercury is the only other terrestrial planet besides the Earth with a planet-wide intrinsic magnetic field. Two recent flybys of the Sun's innermost planet by NASA's MESSENGER spacecraft have revealed that the large-scale morphology of Mercury's internal magnetic field [Anderson et al., 2008] is similar to that of Earth, although Mercury's surface field is two orders of magnitude weaker. Dominantly dipolar and spin-aligned, the fields of both planets possess significant non-dipole moments, manifested as polar and equatorial magnetic "lows". In the case of Earth, the "low" is referred to as the South Atlantic anomaly, a region marked by a growing reverse flux patch at the underlying core surface.

The South Atlantic anomaly is an oval-shaped geographic region in the southern Atlantic Ocean east of Brazil. Because of the relatively weak magnetic field here, the Van Allen belt particles have access to lower altitudes, and the associated increased radiation dose adversely affects satellites traveling through the region. This feature has existed since at least 1840, and is closely tied to the overall decrease of the strength of the Earth's dipole (5% per century) since that time [Jackson and Finlay, 2007]. Another large-scale phenomenon is the rapid motion of the north magnetic dip pole (where the field direction is vertical). Because the horizontal component of the magnetic field in the region of this pole exhibits a very flat gradient, small changes in the field can cause significant displacements of the pole [Mandea and Dormy, 2003].

More generally, changes in the field of internal origin can now be witnessed with unprecedented space and time resolution, providing detailed pictures of fast-changing small-scale structures in the field produced within the core [Hulot et al., 2002, 2007]. The dynamics of these features have been shown to affect the length-of-day variation, and may testify to unexpectedly rapid flow changes in the Earth's core [Olson and Mandea, 2008], a provocative suggestion that needs further validation from the Swarm mission.

The Magnetic Anomaly Map of the World, published in 2007 by UNESCO [Korhonen et al., 2007], was the first global compilation of the wealth of magnetic anomaly information. The map combined CHAMP satellite, aeromagnetic and sea-going surveys, supplemented by anomaly values estimated from a combination of oceanic crustal ages and a magnetic polarity time scale. The measurement domain thus extends from the surface to satellite altitude, and from wavelengths of 10 to 2600 km. A new generation of the map is planned for 2011, and will include many new data from ocean-going surveys, although the southern oceans continue to remain poorly surveyed. The magnetic anomalies represented on this map originate primarily in igneous and metamorphic rocks, in the Earth's crust, and locally, the uppermost mantle.

Complicating the isolation of the internal magnetic fields discussed above are a variety of magnetic fields from sources in Geospace, several of which have been recognized for the first time as a consequence of high-resolution magnetometers and plasma instrumentation on CHAMP. Examples include the magnetic fields associated with regions of dense plasmas [Lühr et al., 2003] or irregularities within the equatorial ionosphere [Stolle et al., 2006] and with gravity-driven electric currents in the ionosphere [Maus and Lühr, 2006]. Electron density anomalies are prominent north and south of the dip equator, especially after sunset. These lead to magnetic field depletions of only 1 part in $10^4$ (Fig 1b), which explains why they were not previously recognized. The magnitude and scale-size of these features falls within the range of crustal anomalies, and earlier models of the crustal magnetic field often contained such spurious signatures. These features can also cause artifacts in main field models, especially in the secular variation and acceleration coefficients, due to the solar cycle dependence of the effect. Because the Swarm satellites will be at two different local times, external field effects, and corresponding induced effects, are more likely to be recognized and isolated. Extensive simulation studies have shown how satellites at multiple local times can be optimized to do the best job of separating internal, external and induced fields.

Newly recognized processes with magnetic signatures are not confined to external effects but include the oceanic lunar semidiurnal ($M_2$) tide [Tyler et al., 2003]. The semidiurnal tide possesses a magnetic signature because seawater is an electrically conducting fluid. The flow of this fluid through the Earth's main magnetic field in turn generates magnetic fields, but does not affect the current flow to any significant degree. The tidal signature was easily recognized because of a clear $M_2$ peak in the intensity spectra over the ocean data collected by CHAMP, in contrast to the land data where the peak was absent. Additionally, a global numerical prediction of these magnetic fields was in good agreement with observations. Of more importance for climate modeling, the magnetic signal associated with oceanic currents should also be measurable by CHAMP, and Swarm. However, the spatial scale of these signals overlaps with those from the core and crust, and they have not yet been isolated.

The mantle is considered to be nonmagnetic because of mineralogy and elevated temperature, but subduction margins may be an exception to this rule. Subducting oceanic slabs release water into overlying continental mantle, thereby transforming peridotite into serpentinite. Serpentinite often contains abundant magnetite, and thermal models suggest that the cold, descending slab cools the mantle to below the Curie-temperature of magnetite. Magnetic and gravity anomalies over subduction zones are commonly seen in satellite anomaly maps. In the Cascadia and Alaskan subduction zones, the depth of the sources of these long-wavelength anomalies has been estimated to be within the mantle [Fig. 1c, Blakely et al., 2005]. Because hydrated mantle responds differently to deformation than unhydrated mantle, and because water released from the slab promotes brittle failure within the slab, models predict a causal connection between intraslab earthquakes and hydrated forearc mantle.

The discovery of new processes with satellite magnetic signatures is expected to continue apace with Swarm. In addition, by making it possible to access the detailed evolution of the field at the core surface over a significant time period, data assimilation procedures may be used to predict the future behavior of the Earth's magnetic field. Work already has begun in that direction, with promising results [Fournier et al., 2007; Liu et al., 2007]. Finally, the local time coverage of the Swarm satellites will significantly advance studies of the 3-D electrical conductivity of the mantle. Conductivity variations often correspond to large-scale variations in water content, and this approach may provide an alternative to seismic techniques for imaging subducted slabs within the mantle.

*Acknowledgments*
We would like to acknowledge Richard Blakely and Eric Donovan for editing.

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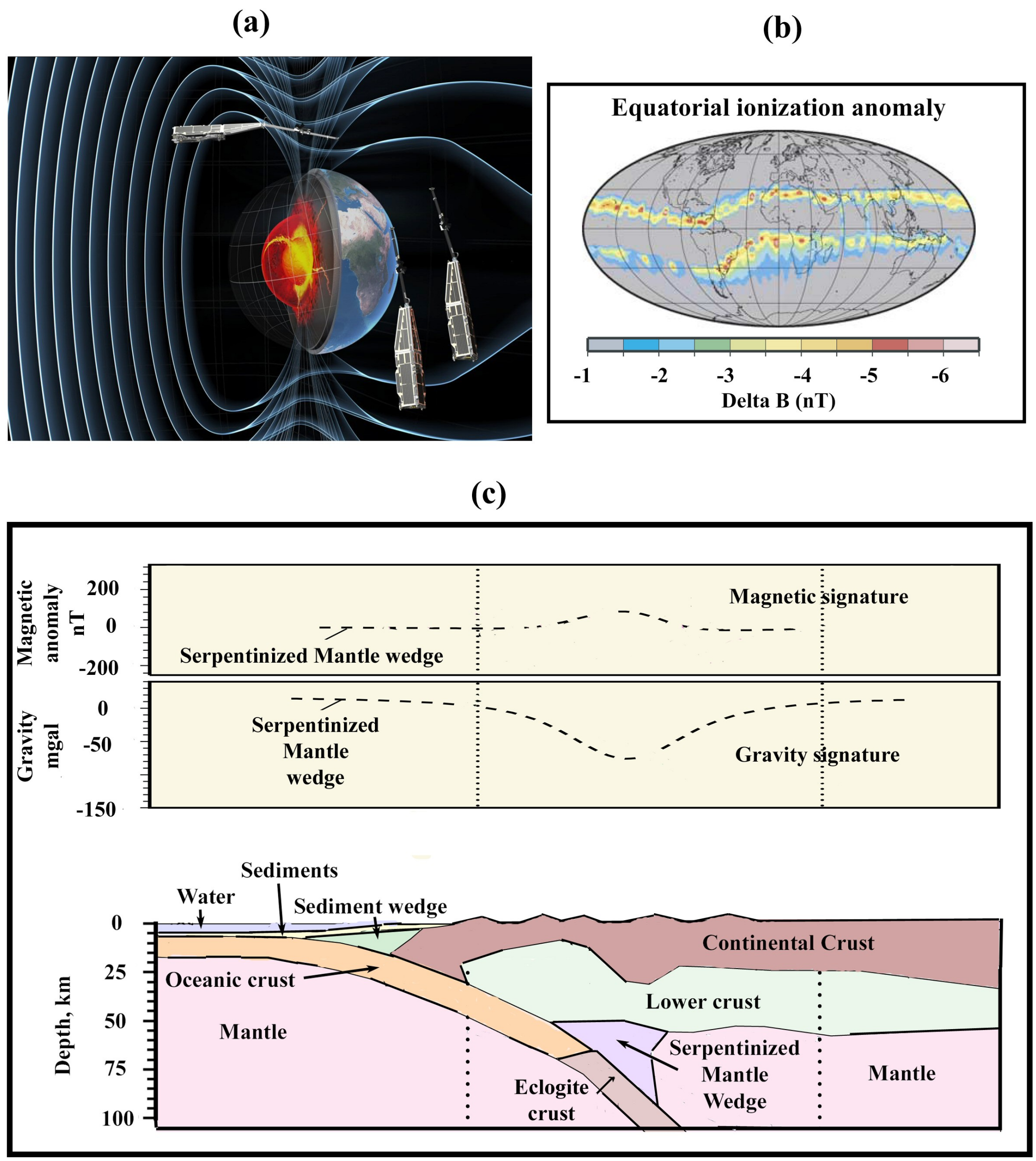


**Figure 1. a)** Schematic of the upcoming Swarm constellation (ESA/AOES Medialab), set within the geomagnetic environment of the Earth b) Magnetic effect of the equatorial ionization anomaly, after sunset at 400 km altitude, 23-27 Oct 2001 (Lühr et al., 2003), c) Crust and upper mantle model of subduction zone and associated serpentinite mantle wedge associated with magnetic and gravity anomalies. Adapted from Blakely et al., 2005.